The Glacier and Land Ice Surface Topography Interferometer (GLISTIN): A Novel Ka-band Digitally Beamformed Interferometer

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Abstract— The estimation of the mass balance of ice sheets and glaciers on Earth is a problem of considerable scientific and societal importance. A key measurement to understanding, monitoring and forecasting these changes is ice-surface topography, both for ice-sheet and glacial regions. As such NASA identified "*ice topographic mapping instruments capable of providing precise elevation and detailed imagery data for measurements on glacial scales for detailed monitoring of ice sheet, and glacier changes*" as a science priority for the most recent Instrument Incubator Program (IIP) opportunities. Funded under this opportunity is the technological development for a Ka-Band (35GHz) single-pass digitally beamformed interferometric synthetic aperture radar (InSAR). Unique to this concept is the ability to map a significant swath impervious of cloud cover with measurement accuracies comparable to laser altimeters but with variable resolution as appropriate to the differing scales-of-interest over ice-sheets and glaciers.

I. Introduction

This paper describes a novel Ka-band (35 GHz) radar for mapping the surface topography of glaciers and ice sheets at high spatial resolution, high vertical accuracy, independent of cloud cover, with a swath-width of 70km. Dubbed the "Glacier and Land Ice Surface Topography Interferometer" (GLISTIN) and depicted in Figure 1, the system is a single-pass, single platform interferometric synthetic aperture radar (InSAR) with an 8mm wavelength, which minimizes snow penetration yet remains relatively impervious to atmospheric attenuation. In contrast to lidars, the instrument will be insensitive to clouds, provide significant swath-widths, cover the poles sub-monthly, and provide inherently variable spatial resolution: high spatial resolution for meter-scale vertical precision on glaciers and coastal regions; coarse spatial resolution for decimeter accuracy on featureless ice sheet interiors. Previous attempts at using millimeter-wave InSAR faced fundamental problems, including limited swath widths and high transmitted power requirements. Our approach overcomes those two major limitations by applying digital beamforming techniques to standard InSAR. Both Ka-band antennas and digital beam forming have been used in various ground-based and airborne applications, however, no antenna systems exist that are substantially similar to the proposed system.

To date, no civilian spaceborne imaging InSAR system has utilized Ka-band. There has also never been, to our knowledge, any digital beam forming radar flown in space. This technology has no alternatives when high resolution and swath is required other than the use of extremely high power transmitters that are impractical from both a technological and power consumption standpoint (we achieve greater than an order of magnitude savings in power through the use of DBF from 14kW to 1kW). Our system also results in a substantial mass savings when compared with a lower frequency system. For example, for equivalent accuracy at 13GHz (WSOA frequency and the highest interferometric radar frequency to date) a boom of nearly 24m would be required as opposed to the 8m of our design.

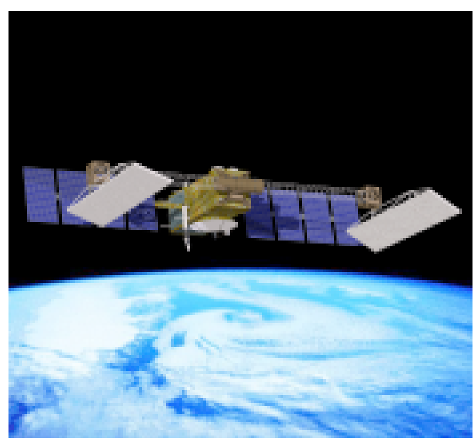

Figure 1: *GLISTIN mission concept.*

The current GLISTIN IIP program will address key technological hurdles of the proposed satellite-based sensor, most notably a large (4x1m) Ka-band digital beam-forming antenna array, systematic calibration and data processing. To guide the technology development, the initial stage of this program has focused on the development of a mission scenario, science, system and instrument requirements. In this paper, we will cover the derived requirements and expected performance of the spaceborne system in order to provide context for the ongoing technology development efforts, and introduce the strategy for the cohesive ground-based demonstration that will be the culmination of the GLISTIN IIP effort.

Section II will discuss the science motivation and requirements for the mission scenario. This will be followed by the nominal orbit selection and characteristics in Section III. Section IV will take the science requirements and roll them down into system level and subsequently subsystem level requirements. These requirements drive the specifications for the technology development activities of this IIP, which will be overviewed in Section V.

II. Science Motivation and Requirements

The Greenland and Antarctic ice sheets together hold enough ice to raise global sea level by 80 m. The annual exchange of mass on the ice sheets is equivalent to 8mm/yr sea level, so that any fluctuation in that level of exchange is significant on a global scale.

Recent airborne laser altimetry campaigns, satellite radar altimetry, and ICESat altimetry in Greenland and Antarctica have revealed glacier thinning rates ranging from a few cm/yr in the interior to meters or tens of meters per year at the coast, along channels occupied by outlet glaciers. Most interior changes are explained in terms of fluctuations in snowfall, whereas large coastal changes are caused by glacier ice dynamics. While coastal changes dominate in Greenland and West Antarctica, changes in interior accumulation have a significant impact on total mass balance in East Antarctica; it is therefore important to monitor both interior and coastal regions. In order to obtain meaningful results on ice sheets based on existing observations and interpretation of the results, we estimate that surface elevation needs to be measured with a sub-10 cm accuracy on a 1 km scale in the interior, and a few tens of cm at a spatial resolution of 100m at the coast, where the km-scale dimensions of glaciers demand finer resolution. If these measurement objectives are achieved - namely better than 1m at 100 m resolution on glacier ice along the coast, less than 10 cm at 1 km resolution in the interior - one will be able to improve current estimates of ice sheet mass balance obtained from other altimetry techniques significantly. Compared with satellite radar altimetry, this instrumentation will be able to resolve coastal changes more accurately (errors could be larger than 100% at present). While measuring height changes over time is certainly a most important measurement to be made, there is also considerable value in assembling precise and complete topography of land-ice covered areas (arguing for a mapping sensor). This information provides constraints on the driving stress of the ice, drainage basins, and roughness statistics, as well as surface features that can be tracked through time to detect ice motion and acceleration.

Table 1 summarizes the science measurement and coverage requirements. Compared with laser altimetry, radar interferometry would provide comprehensive and dense coverage of the ice sheets at a comparable level of accuracy, and essentially independent of cloud cover and solar illumination. significant on the global scale.

Table 1: *Science and coverage requirements*

Topic	Requirement
Coverage	Monthly to bi-monthly coverage of glaciers and ice-sheets
	Complete coverage of Antarctica and Greenland (a hole at the North Pole is acceptable)
Glaciers	100mx100m posting
	1m relative height accuracy
Ice-sheets	1km x 1km posting
	10 cm relative height accuracy

III. Orbit Selection

Based on the fundamental system concept combined with the science coverage requirements, an orbit of approximately 600km was selected with a resulting nominal ground swath of 70km (incidence angles ranging from 18.6-25.2 degrees). Initially sun-synchronous orbits were investigated and rejected as it was discovered that there was an unavoidable and unacceptable gap in coverage over both Poles. The coverage requirements in Table 1 calls for full coverage of the South Pole – however a "hole" at the North Pole is acceptable: in a non-sunsynchronous near polar orbit, with a side-looking instrument a coverage gap is inevitable at one of the poles. Either a left-looking instrument in an inclination of 88 degrees or a right-looking instrument at an inclination of 92 degrees is acceptable providing full coverage over Antarctica. Temperate glaciers are found close to the equator and it takes at least 571 swaths of 70 km each to cover the equator without gaps. This takes 39 days at 600km altitude, satisfying the monthly-bimonthly coverage requirement. The orbit was optimized to provide an evenly spread coverage after 1/2 repeat cycle and therefore guarantee two acquisitions every 1/2 repeat cycle above 60 degrees latitude. Based on this the best altitude/orbit count was a 605.7 km altitude, with 593 orbits/repeat cycle and a 40 day repeat period. Figure 2 summarizes the revisit coverage of the selected orbit as a function of latitude. It is notable that high latitudes (>60 degrees) are imaged every 10 days or better on average.

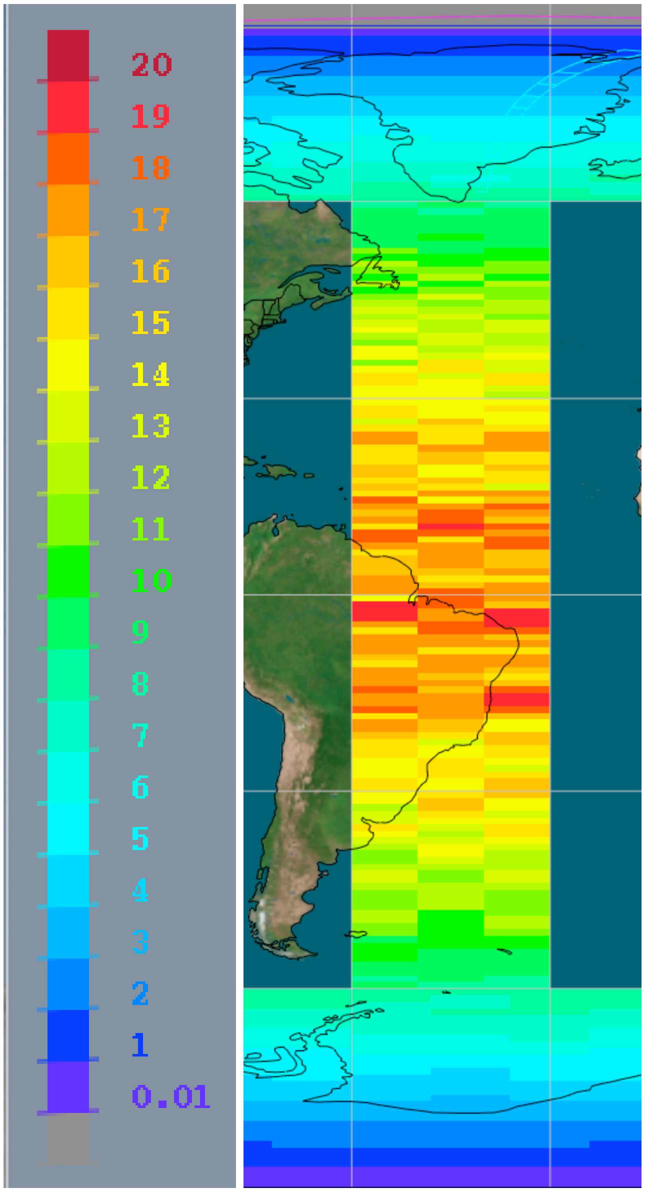

Figure 2: *Illustration of the average revisit time as a function of latitude*

A consequence of employing a non-sunsynchronous orbit is that the spacecraft will transition into and out of eclipses.Eclipsesimpact both power resources and the thermal stability of the instrument itself. For any given initial sun geometry there will be 'eclipse seasons' when the satellite will go through the Earth's shadow for up to 35 min/orbit. During these seasons the average incident solar power will be reduced by up to 35% and batteries will be required to operate the radar during these eclipses.

From a thermal stability perspective, one can consider that during transitions into and out of eclipse, the system will suffer from a "thermal shock". A first-order dynamic thermal analysis based on very simple models of the antenna arrays arrived at a stabilization time of roughly 5 minutes. A worst case assumption is that data within 5 minutes of a transition is unusable due to the nonlinear behavior of the antenna deformations and other system temperature sensitive behavior. The impact of this on data collection is summarized in Figure 3. In this figure the affected latitude bands as a function of elapsed days is plotted. The time that data is lost lies in the regions between the "transition start" and "transition end" lines. However, the vast majority of the time data is only lost either on ascending or descending passes, leaving one direction unaffected. The only times when both ascending and descending data are lost is where one of the lines is shown "pegged" at +/-90 degrees (actually transitioning from descending to ascending or vice versa). The data loss is maximum 2 months for 5 degrees about the pole (for a nadir viewing geometry – for the side-looking configuration the data loss is less at the South Pole and greater at the North Pole).

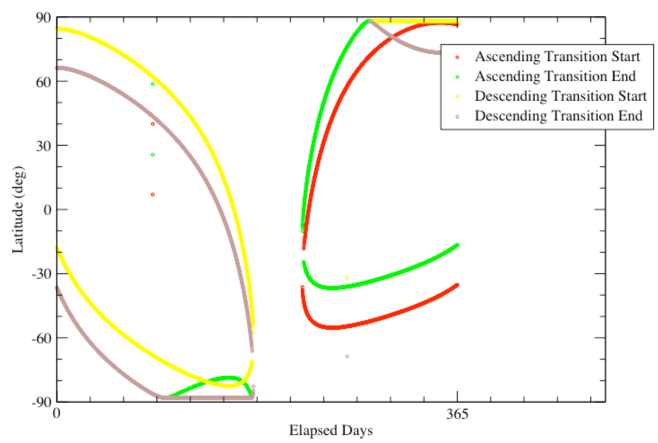

Figure 3: *Profile of eclipse transition times over a year (exact timing determined by choice of initial conditions).*

IV. SPACEBORNE INSTRUMENT DESIGN

A Ka-band single-pass InSAR is ideally suited to meet the requirements for glacier and ice sheets. Single-pass imaging radar interferometry has unique capabilities in providing fine resolution, topographic mapping over a wide swath independent of solar illumination. A Ka-band (35GHz) center frequency maximizes the single-pass interferometric accuracy (proportional to the wavelength), reduces snow penetration (when compared with lower frequencies), and remains relatively impervious to atmospheric attenuation.

Figure 1 illustrates the measurement configuration whereby two antennas – displaced in the cross-track direction - view the same region on the ground. The interferometric combination of data received on the two antennas allows one to resolve the path-length difference from the illuminated area to the antennas to a fraction of a wavelength. From the interferometric phase the height of the target area can be estimated. Therefore, an InSAR system is capable of providing not only the position of each image point in along-track and slant range as with a traditional SAR, but also the height of that point through interferometry. The height precision is a function of the baseline length, the system frequency and the radar signal to noise ratio [1]. While the millimeter-wave center frequency maximizes the interferometric accuracy from a given baseline length, the high frequency also creates a fundamental problem of swath coverage versus signal-to-noise ratio. While the length of SAR antennas is typically fixed by mass and stowage or deployment constraints, the width is constrained by the desired illuminated swath width. As the across-track beamwidth – which sets the swath size – is proportional to the wavelength, a fixed swath size equates to a smaller antenna as the frequency is increased. This loss of antenna size reduces the two-way antenna gain to the second power, drastically reducing the signal-to-noise ratio of the SAR system.

To overcome this fundamental constraint of high frequency SAR systems, we will use digital beamforming (DBF) techniques to synthesize multiple simultaneous receive beams in elevation while maintaining a broad transmit illumination. Through this technique we will preserve a high antenna gain on receive, reduce the required transmit power, and thus enable high frequency SARs, and high precision InSAR from a single spacecraft.

A. System Design Parameters

We have used the science requirements to design a radar system capable of simultaneously meeting all of the measurement requirements. The system parameters are summarized in Table 2. We have chosen a 0.063 m x 4.0 m transmit antenna to illuminate 7 degrees in elevation. At a boresight incidence angle of 22 degrees this results in a ground swath of 70 km. On receive, the full swath is synthesized as 16 simultaneous subswaths in elevation using DBF over the full receive antenna (1 x 4 m comprised of an array of sixteen 0.063 m x 4 m antenna “sticks” in elevation). One fundamental consideration of using an elevation array is the trade between the size, or number of “sticks” and the ability to steer the array due to the presence of grating lobes. In order to avoid grating lobes the array must be critically sampled spatially ($\lambda/2$). In the case of GLISTIN, the inter-stick spacing is ~7.4λ resulting in grating lobes at +/- 7 degrees. When we steer off-boresight the grating-lobe levels become significant as they are no longer rejected sufficiently by the element pattern of the sticks. However, because the steering occurs in elevation, we are easily able to range-gate out the ambiguous returns. By simple geometry, the local slope of the surface could cause the grating-lobe to occur at the same range as the desired viewing angle. However, in this scenario the scene would not only need to have a slope of ~18 degrees (quite possible for glaciers) but also to extend for 42km for a total height of 14km, a situation not realistic for the Earth surface.

Table 2: *Fundamental system parameters for the spaceborne interferometer*

Parameter	Units	Quantity
Peak transmit Power	kW	1.5
Frequency	GHz	35
Bandwidth	MHz	80
Antenna Length	m	4
“stick” height	m	0.063
Number of sticks	#	16
Total Array Height	m	1.01
Pulsewidth	us	25
PRF	kHz	4
Interferometric baseline	m	8
Polarization		Horizontal
Swathwidth	km	70
Incidence angle range	degrees	18.6-25.2

The polarization of the antenna is chosen to be horizontal. There is little by way of off-nadir backscatter measurements of snow and ice at Ka-Band, and we based our decision on the models proposed in Ulaby and Dobson [2]. Ulaby and Dobson indicate little difference in backscatter strength between vertical and horizontal polarizations, and there is no geophysical evidence to suggest a preference for one over the other. However, the antenna slot mutual coupling for horizontal polarization is superior and for this reason horizontal polarization was chosen.

The peak transmit power is 1.5kW, which is within the realm of currently available technology. The pulse repetition frequency is 4 kHz to satisfy critical sampling requirements. The bandwidth is kept relatively low (40MHz) to minimize data-rates yet satisfy glacial resolution goals. Despite this, the data-rate still presents a substantial challenge that we will address as a later part of this program.

B. Key Requirements Derivation

Within this program, requirement derivation serves the purpose of determining the specifications for the technology demonstration and development. The instrument requirements flow directly from the science requirements via instrument performance and resolution. In turn the instrument error budget is used to sub-allocate perfornamce to subsystems. These errors comprise:

1. random errors due to thermal noise, ambiguities and multiplicative noise ratios
2. systematic errors
3. pointing errors

Table 3 summarizes the error budget rollup across the swath for the most stringent scenario; a 1km x 1km posting for wet snow and with a 5dB margin in signal to noise ration (SNR). Note that media (atmospheric and surface penetration) errors are currently ignored. One can see that the budget is very tight to meet the 10cm height accuracy requirement across the swath. It is likely the height precision will be improved due to the pessimistic nature of the assumptions. However the systematic/calibration errors are still significant contributors and levy stringent requirements upon the overall calibration and are very similar in magnitude to that derived for the Wide Swath Ocean Altimeter (WSOA) mission [3]. As a topic of ongoing work, we will adapt the extensive WSOA calibration analysis to the GLISTIN scenario in order to address how, in a mission context we might meet the systematic error budget.

Table 3: *Systematic error budget summary as a function of cross-track distance (CTD). Errors are in cm.*

Error Source \ CTD [km]	185	210	230	245
Height Precision	7.8	5.1	5.4	7.5
Systematic/Calibration Error	4.7	5.5	6.1	6.6
Total without POD	9.1	7.5	8.1	10.0

Figures 4 and 5 show the height precision due to SNR, ambiguities and multiplicative noise ratio contributions, predicted across the swath for the ice-sheet (1km x 1km, 10 cm height error requirement) and the glacier (100m x 100m, 1m height error requirement) postings. The scalloping effect shows the profile of the digitally beamformed subswaths. One can realistically expect dry snow on the interior ice-sheet regions, and so the more optimistic curve is likely. Note that the systematic errors summarized in Table 3 do not scale with posting, and so while they are a significant contributor for the 10cm ice-sheet accuracy requirement, they are minimal when compared with the 1m glacial requirement.

The system performance predicted in Figures 4 and 5 is based on instrument requirements levied on the antenna, RF and digital subsystems, to be built, tested, integrated and demonstrated as part of this IIP. The next section summarizes the overall technology demonstration goals and effort including the subsystem requirements. Where possible, these requirements are identical to the spaceborne requirements and any deviations from these are noted.

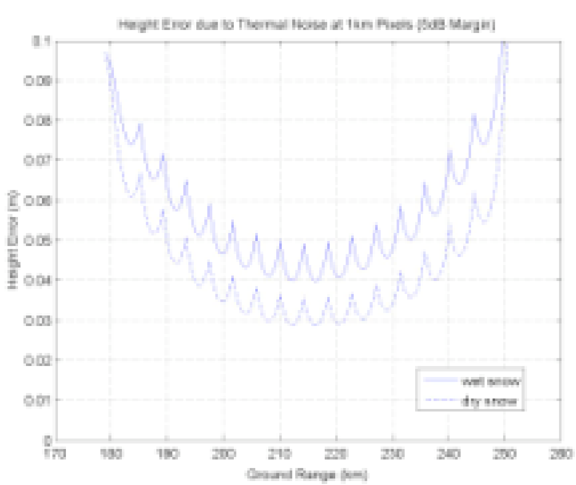

Figure 4: *Height error across the swath due to random contributions (thermal, ambiguities and multiplicative factors).*

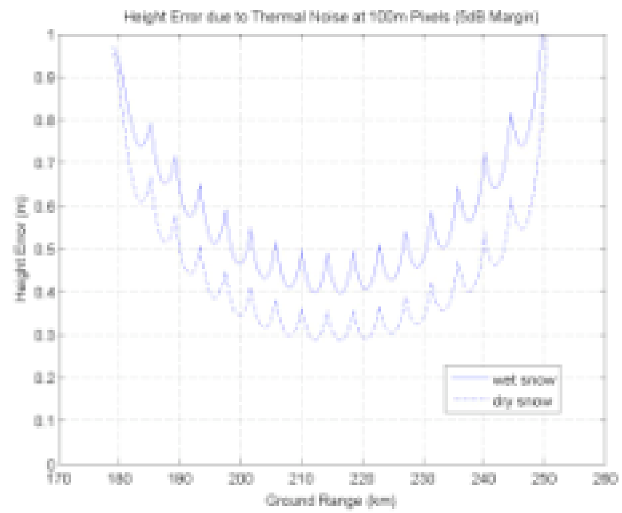

Figure 5*: Height error across the swath due to random contributions (thermal, ambiguities and multiplicative factors).*

V. Demonstration and Technology Development

The overall objective of this program is to develop and demonstrate the key technology of the GLISTIN concept including the end-to-end measurement technique and associated processing. A block diagram of the key development, the digital antenna array, is shown in Figure 6. The antenna will be integrated into a simple radar system, mounted on a positioner at a site overlooking the JPL facility, and used to collect an interferometric image. The demonstrated antenna will be a 1m long (0.25 of the spaceborne length) full-height array (1m, 16 "sticks"). Dedicated digital receivers will be integrated with each antenna stick and a 0.5m interferometric baseline will be synthesized by interfering the beamformed returns from the upper and lower halves of the array. An interferometric image will be produced through a combination of digital beam-forming for the fine-scale coupled with elevation scanning on a coarse scale using the positioner. Azimuth scanning will be achieved by rotating the positioner in that axis.

The two key sub-elements of the demonstration are the antenna aperture and the integrated digital receiver. These efforts are summarized subsequently and as the development matures will be the subject of future reporting. All other support hardware is for the demonstration but not considered a technology challenge within the context of the IIP.

A. Antenna Requirements and Technology

The antenna requirements are summarized in Table 4. The only deviations from the spaceborne case arise due to the fact that the length is 1/4 size and that the boresight angle is dependent on the demonstration topography. The azimuth alignment requirement is therefore reduced by a factor of four over the spaceborne requirement.

The technology chosen for this application is a slotted waveguide implementation, considered the best option given efficiency and weight considerations. Other primary contenders were a microstrip patch array (lossy and higher mass) and horns with a coaxial power divider (heavy costly and bulky). This development will demonstrate that such an electrically larger antenna can be manufactured and identify a path to meet flight implementations.

Table 4: *Summary of antenna demonstration requirements*

Parameter	Unit	Value
Boresight pointing angle	Degrees	TBD +/- 0.5
Azimuth pointing alignment	Degrees	<0.04
Number of "sticks"	#	16
Elevation beamwidth of each stick	Degrees	At least 6.8
Antenna length	m	1
Peak side lobe level	dBc	-13
RMS flatness of each antenna	urad	<160
Far-field cross polarization level	dB	>-20

B. Ka-band Digital Receiver

Table 5 summarizes the receiver requirements. The timing differs due to the different measurement geometry, and the bandwidth is larger for better range-discrimination in the field application. In other respects the receiver design is consistent with the flight requirements.

In order to perform DBF, a digital receiver is required for each receive subarray. Our design focuses on implementing small and low power devices with the principle that the outcome be as "flight-like" as possible including attention to parts selection, electrical, mechanical and thermal design. Toward this end, a fundamental design principle is to minimize the number of downconversion stages and therefore the amount of local oscillator (LO) power required, the associated, often bulky components and the need to distribute multiple LO signals to all digital receivers. As shown in Figure 7, our design will achieve this by having only a single downconversion stage to a low (1.26GHz) frequency. Furthermore, by using mixers that can be pumped at one half of the LO frequency, the generation and distribution of the LO is greatly simplified.

The downconverted (1.26GHz) signal is directly digitized at 100MHz, capturing the full-bandwidth via aliasing. Although this approach requires a faster and thus more power hungry ADC than the standard, unaliased sampling technique, this is offset by the benefits of avoiding the additional downconversion stage and achieves our goal of a simpler, smaller and more "flight-worthy" design.

The final step in the digital receiver is a field programmable gate array (FPGA) which is fed by the ADC. In the initial implementation this FPGA will be simply an interface and a data buffer. However, this FPGA will be sized to allow the onboard range compression techniques that can be added to this receiver for an end-to-end demonstration.

Table 5: *Digital receiver demonstration & flight unit requirements.*

Parameter	Requirement	
	Flight	**Demo**
Bandwidth	40 MHz	80 MHz
Receive Window	178 us	50 us
PRF	4 kHz	500 Hz
Noise Figure	4.5 dB	4.5 dB
Effective # of Bits	> 7 bits	> 7 bits
ADC Jitter	< 0.01 ns	< 0.01 ns
Receive Filter Amplitude Deviation	< 0.3 dB	< 0.3 dB
Receive Filter Phase Ripple RMS Error	< 2 deg	< 2 deg

VI. SUMMARY

This paper summarizes a new concept for ice-surface topography measurement that applies mm-wave radar technology and digital beamforming techniques to overcome shortcomings of existing techniques. Specifically, the GLISTIN system holds the potential for high-accuracy swath mapping of ice-sheets and glaciers overcoming current coverage, resolution and visibility limitations of competing techniques. Initial system designs have identified key driving requirements that must be met in order to meet the science requirements. The need for stringent calibration of the systematic errors in the mission scenario will be the topic of future work.

Technology development efforts that address the antenna manufacturing and performance, and the design of integrated receivers are underway and will not only serve to address these items, but ultimately will be integrated into a complete radar and used to demonstrate the full concept end-to-end.

ACKNOWLEDGMENT

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REFERENCES

[1] E. Rodriguez, and J. Martin,*Theory and design of interferometric synthetic aperture radars*, IEE Proceedings-E, Vol.139, No.2, April

[2] F.T. Ulaby & M. C. Dobson, *Handbood of Radar Scatttering Statistics for Terrain* , Artech House,Norwood MA, 1989.

[3] B.D. Pollard, E. Rodríguez, L. Veilleux, T. Akins, P. Brown, A. Kitiyakara, M. Zawadski, S. Datthanasombat and A. Prata, Jr, 2002: *The wide swath ocean altimeter: radar interferometry for global ocean mapping with centimetric accuracy*, Proceedings of the 2002 Aerospace Engineering

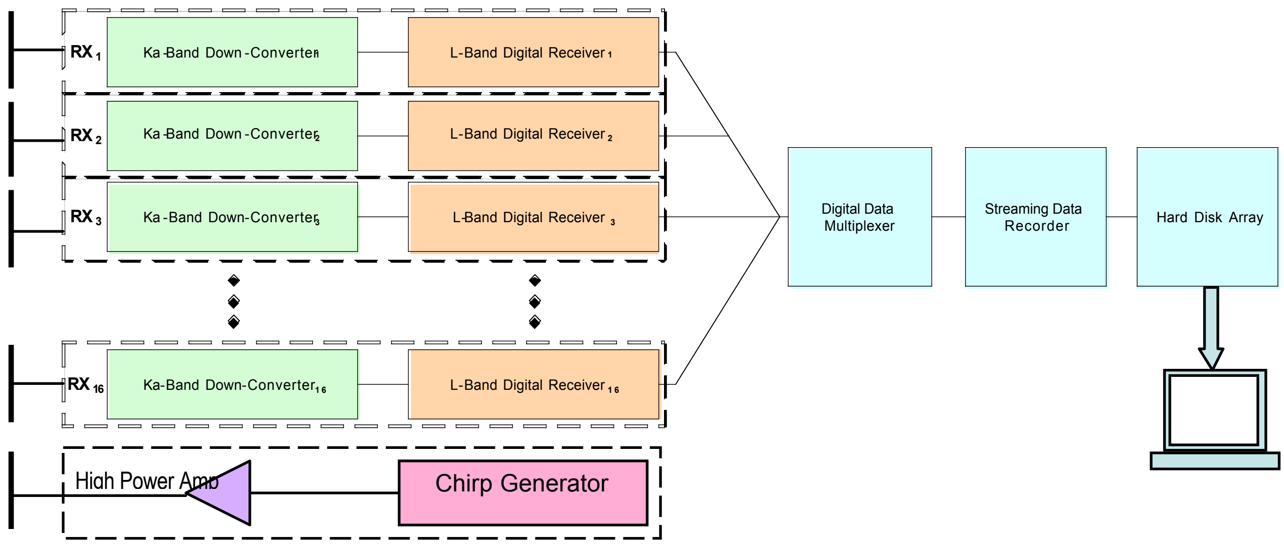

Figure 6: *Demonstration configuration*

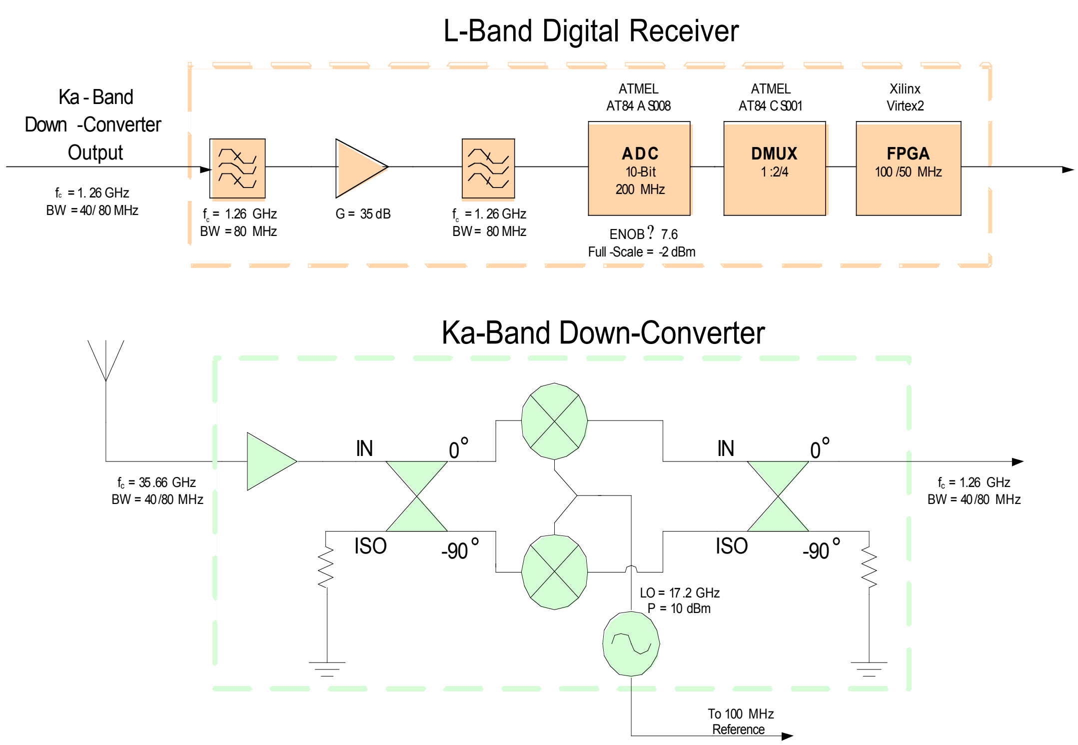

Figure 7: *Ka-band digital receiver schematic*